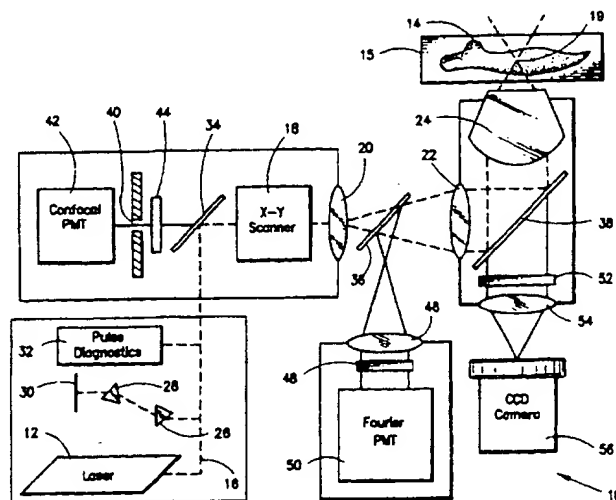




INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification ⁶: G01N 21/64	A1	(11) International Publication Number: WO 97/11355 (43) International Publication Date: 27 March 1997 (27.03.97)
(21) International Application Number: PCT/US96/14519 (22) International Filing Date: 18 September 1996 (18.09.96) (30) Priority Data: 60/003,957 19 September 1995 (19.09.95) US (71) Applicant (for all designated States except US): CORNELL RESEARCH FOUNDATION, INC. [US/US]; 20 Thornwood Drive, Ithaca, NY 14850 (US). (72) Inventors; and (75) Inventors/Applicants (for US only): WEBB, Watt, W. [US/US]; 9 Parkway Place, Ithaca, NY 14850 (US). XU, Chris [CN/US]; 2203 Hasbrouck Apartment, Ithaca, NY 14850 (US). (74) Agents: BLAKE, William, A. et al.; Jones, Tullar & Cooper, P.C., Suite 1002, 2001 Jefferson Davis Highway, Arlington, VA 22202 (US).		(81) Designated States: AL, AM, AT, AU, AZ, BB, BG, BR, BY, CA, CH, CN, CZ, DE, DK, EE, ES, FI, GB, GE, HU, IL, IS, JP, KE, KG, KP, KR, KZ, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, TJ, TM, TR, TT, UA, UG, US, UZ, VN, ARIPO patent (KE, LS, MW, SD, SZ, UG), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, ML, MR, NE, SN, TD, TG). Published <i>With international search report.</i>

(54) Title: MULTI-PHOTON LASER MICROSCOPY**(57) Abstract**

A laser scanning microscope (10) produces molecular excitation in a target material (14) by simultaneous absorption of three or more photons to thereby provide intrinsic three-dimensional resolution. Fluorophores having single photon absorption in the short (ultraviolet or visible) wavelength range are excited by a beam (16) of strongly focused subpicosecond pulses of laser light of relatively long (red or infrared) wavelength range. The fluorophores absorb at about one third, one fourth or even smaller fraction of the laser wavelength to produce fluorescent images of living cells and other microscopic objects. The fluorescent emission from the fluorophores increases cubically, quartically or even higher power law with the excitation intensity so that by focusing the laser light, fluorescence as well as photobleaching are confined to the vicinity of the focal plane. This feature provides depth of field resolution comparable to that produced by confocal laser scanning microscopes, and in addition reduces photobleaching and phototoxicity.

FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AM	Armenia	GB	United Kingdom	MW	Malawi
AT	Austria	GE	Georgia	MX	Mexico
AU	Australia	GN	Guinea	NE	Niger
BB	Barbados	GR	Greece	NL	Netherlands
BE	Belgium	HU	Hungary	NO	Norway
BF	Burkina Faso	IE	Ireland	NZ	New Zealand
BG	Bulgaria	IT	Italy	PL	Poland
BJ	Benin	JP	Japan	PT	Portugal
BR	Brazil	KE	Kenya	RO	Romania
BY	Belarus	KG	Kyrgyzstan	RU	Russian Federation
CA	Canada	KP	Democratic People's Republic of Korea	SD	Sudan
CF	Central African Republic	KR	Republic of Korea	SE	Sweden
CG	Congo	KZ	Kazakhstan	SG	Singapore
CH	Switzerland	LI	Liechtenstein	SI	Slovenia
CI	Côte d'Ivoire	LK	Sri Lanka	SK	Slovakia
CM	Cameroon	LR	Liberia	SN	Senegal
CN	China	LT	Lithuania	SZ	Swaziland
CS	Czechoslovakia	LU	Luxembourg	TD	Chad
CZ	Czech Republic	LV	Latvia	TG	Togo
DE	Germany	MC	Monaco	TJ	Tajikistan
DK	Denmark	MD	Republic of Moldova	TT	Trinidad and Tobago
EE	Estonia	MG	Madagascar	UA	Ukraine
ES	Spain	ML	Mali	UG	Uganda
FI	Finland	MN	Mongolia	US	United States of America
FR	France	MR	Mauritania	UZ	Uzbekistan
GA	Gabon			VN	Viet Nam

MULTI-PHOTON LASER MICROSCOPY

Background Of The Invention

The present invention relates to a laser microscopy technique which produces molecular excitation in a target material by simultaneous absorption of three or more photons. The invention is an improvement over the two-photon laser microscopy technique disclosed in U.S. Patent No. 5,034,613 to Denk et al. (hereinafter, the '613 patent), and this patent is hereby incorporated by reference.

The '613 patent discloses a laser scanning microscope which produces molecular excitation in a target material by simultaneous absorption of two photons to provide intrinsic three-dimensional resolution. Fluorophores having single photon absorption in the short (ultraviolet or visible) wavelength range are excited by a stream of strongly focused subpicosecond pulses of laser light of relatively long (red or infrared) wavelength range. The fluorophores absorb at about one half the laser wavelength to produce fluorescent images of living cells and other microscopic objects. The fluorescent emission from the fluorophores increases quadratically with the excitation intensity so that by focusing the laser light, fluorescence and photobleaching are confined to the vicinity of the focal plane. This feature provides depth of field resolution comparable to that produced by confocal laser scanning microscopes, and in addition reduces photobleaching. Scanning of the laser beam, by a laser scanning microscope, allows construction of images by collecting two-photon excited

fluorescence from each point in the scanned object while still satisfying the requirement for very high excitation intensity obtained by focusing the laser beam and by pulse time compressing the beam.

5 The focused pulses also provide three-dimensional spatially resolved photochemistry which is particularly useful in photolytic release of caged effector molecules.

A drawback to the two-photon laser microscopy technique disclosed in the '613 patent is that its applications are limited by the available laser technology. In particular, the two-photon technique requires use of a laser at specific wavelengths, depending upon the application, so
10 that the sum of energy levels of the two photons provides the specific energy level needed to generate the desired fluorescent emission. Unfortunately, some laser microscopy applications would require use of a laser having a wavelength
15 which is not technologically feasible at the present time. For example, excitation of chromophores that have very short wavelength absorption, such as amino acids and nucleic acids, would require a laser having a 540 nm wavelength
20 using the two-photon technique, and such a laser does not exist at the present time.

Summary Of Invention

The present invention provides a solution to the aforementioned problem through the application
30 of three or more photon excitation to laser scanning fluorescence microscopy and to spatially resolved photo-chemical processing, such as caged reagent activation for micropharmacology and

polymer cross linking for 3-d optical information storage.

Because three-photon induced fluorescence obeys a cubic dependence on excitation intensity and four photon excitation obeys a quartic dependence, both provide intrinsic three-dimensional resolution in laser scanning microscopy. Although such 3-d resolution has already been achieved by the nonlinear microscopy technique based on two-photon excitation disclosed in the '613 patent, three-photon excitation provides a unique opportunity to excite molecules normally excitable in the UV range (230-350 nm) with near IR light (700-1100 nm). Interesting biomolecules, such as the amino-acids tryptophan and tyrosine, the neurotransmitter serotonin and nucleic acids, have one-photon absorption peaks at approximately 260-280 nm, and fluorescence can be excited in these biomolecules by three and four photon excitation. The advantages of using long wavelength, near IR light are possibly less photodamage to living cells and conveniently available solid state femtosecond laser sources for deep UV absorbers. In practice, the configuration of three-photon laser scanning microscopy can be identical to the existing two-photon systems. However, because three-photon and two-photon absorption spectra are in general quite different, the combination of two- and three-photon excited fluorescence microscopy extends the useful range of the laser systems currently employed in two-photon microscopy.

A particularly advantageous application of three or more photon excitation is the replacement of excimer lasers for certain applications which

require absorption of wavelengths around 200 nm. Three and four photon excitation by lasers generating much longer wavelengths (say 550-900 nm) should provide similar energy absorption and provide 3-d spatial resolution as well. Because excimer lasers are extremely expensive and user unfriendly, several photon excitation could be highly desirable.

The practicality of the proposed three-photon microscopy depends crucially on the three-photon fluorescence excitation cross-sections of various fluorophores and biomolecules. However, very few three-photon absorption cross-sections have been reported. A simple calculation based on perturbation theory shows that three-photon excitation would typically need <10 times the peak intensity currently used with two-photon excitation technique to achieve a comparable level of excitation. This required intensity level can be easily accessed by femtosecond laser sources, such as the modelocked Ti:sapphire laser. Three-photon induced fluorescence of tryptophan and serotonin has been observed at excitation wavelengths between approximately 800 and 900 nm using a modelocked Ti:sapphire laser. The measured fluorescence obeys an expected cubic law dependence on excitation intensity. Measurements of fluorescence power of the calcium indicator dye Fura II at an excitation wavelength (approximately 911 nm) well below the expected three-photon excitation optimum, showed that satisfactory fluorescence images should be obtainable at only ~5 times the laser power required for two photon excitation of Fura II at its optimum excitation wavelength (approximately 730 nm). The estimated

three-photon fluorescence excitation cross-section from these preliminary results shows that three-photon laser scanning microscopy can be done with a reasonable level of excitation power. How widely applicable this approach will be remains to be determined. Four-photon excitation may be limited by the onset of strong one-photon absorption by water above about 1000 nm.

Studies of molecular excitation of fluorescence by three or more photon processes are rare because the excitation cross sections have been expected to be quite small. Thus, useful rates of excitation usually require very high instantaneous illumination intensities. A simple extrapolation of multiphoton cross sections is suggested by the pattern of matrix elements products in the perturbation theory solutions of the quantum mechanics of the dipole transition probability for molecular excitation by a radiation field. Basically, the multiphoton processes require three or more photons to interact with the molecule (within the cross sectional area of a molecule, $A \sim 10^{-16} \text{ cm}^2$) and simultaneously (within a time interval determined by the life times of intermediate states, $\delta t \sim 10^{-16} \text{ s}$). This short coincidence time is limited by the large energy uncertainties introduced by the perturbation theory energy denominators.

Fluorescence excitation by several photons does not significantly increase laser microscopy resolution because the longer excitation wavelength (for a given fluorophore) decreases resolution by about as much as it is increased by raising the one-photon point spread function to the power n for several-photon processes. Were it

not for the wavelength factors, the increase in resolution of three photon excitation would be essentially the same as that incurred by adding an ideal confocal spatial filter to two photon microscopy.

Recent reports of unexpectedly large three-photon cross sections have been found in the course of research directed toward enhancing optical limiting absorption (which is intended to provide variable shades for protection of human vision from excessively brilliant light flashes). Recently, a three photon absorption cross section of about $10^{-75} \text{ cm}^6\text{s}^2$ has been reported for absorption and fluorescence of 2,5-benzothiazol-3,4-didecyloxy thiophene in tetrahydrofuran. Another recent experiment shows three photon excitation of fluorescence from a conjugated organic polymer. This process, however, appears to involve two excitation states unlike most fluorescence excitation. Although the conditions of these experiments are hardly suitable for laser scanning fluorescence microscopy or for most microphotochemistry, the large cross sections are promising. Note, however, that such large cross-sections are not essential for three or more photon microscopy.

The excitation wavelength dependence of the rate of photodamage to living cells during fluorescence microscopy and photomicropharmacology is largely unknown and may vary greatly for different applications. Empirical studies have shown that two-photon excitation elicits far less damage than one-photon excitation for comparable fluorescence image acquisition. It is not clear whether further improvement can be

made by stepping up to three- or four-photons for excitation. With the aid of such knowledge and the knowledge of the nonlinear absorption spectra, it is conceivable that the optimum excitation mode can be determined and utilized for each individual system in the future. A particularly appealing possibility is the use of one laser wavelength to induce photochemistry by three photon excitation and concurrently two-photon excitation of an accompanying fluorescence signal. Three-photon excitation seems quite likely to become a useful enhancement of the existing two-photon excitation technique but seems unlikely to replace it.

Alternatively, for microscopic photochemical activation, photoablation and optical surgery, the photo excitation can be advantageously accomplished by multi-photon excitation of intrinsic chromophores or even added chromophores that have very short wavelength absorption such as amino acids and nucleic acids. Multi-photon excitation allows the selection of more available lasers providing subpicosecond pulses at long wavelengths and long wavelength light transmission to the microscopic focal volume where photo excitation is desired.

Brief Description of the Drawings

The foregoing and additional features and advantages of the present invention will become apparent from the following detailed description of a preferred embodiment thereof, taken in conjunction with the accompanying drawings, in which:

FIG. 1 is a diagrammatic illustration of a laser scanning microscope utilized in accordance

with a preferred embodiment of the present invention; and

FIGs. 2 and 3 are graphs of the average fluorescence intensity versus the applied peak
5 laser flux density obtained utilizing three-photon excitation of Fura-2 and Indo-1, respectively.

Best Mode For Carrying Out The Invention

Turning now to a detailed description of a preferred embodiment of the present invention,
10 FIG. 1 illustrates in diagrammatic form a conventional laser scanning microscope 10 which includes three detection alternatives. A subpicosecond pulsed laser source 12 provides the necessary excitation of a specimen or target
15 material 14 which is positioned on a movable stage or other suitable support 15. The laser 12 may be, for example, a colliding pulse, mode-locked dye laser or a solid state laser which can generate pulses of light having a wavelength in
20 the red region of the spectrum, for example about 630 nm, with the pulses having less than 100 fsec duration at about 80 MHz repetition rate. Other bright pulsed lasers may also be used to produce light at different relatively long wavelengths in
25 the infrared or visible red region of the spectrum, for example, to generate the necessary excitation photon energies whose sum will equal the appropriate absorption energy band required by the fluorophores in the specimen. In a single
30 photon excitation technique, these would be excited by absorption of a single photon in the spectral region having wavelengths approximately one third or one fourth the wavelength of the incident light, for three and four photon

excitation, respectively. Thus, for example, three photons in the visible red region at 945 nm would combine to excite a fluorophore which normally absorbs light in the ultraviolet region at 315 nm, while three photons at 1070 nm would excite a molecule which absorbs at 357 nm in the visible light region.

In a modified form of the invention, the single wavelength laser 12 can be replaced by two or more different long wavelength laser sources so that the incident light beam consists of two or more superimposed pulsed light beams of high instantaneous power and of different wavelengths. The wavelengths of the incident beam are selected to excite a fluorophore which is absorbent at a short wavelength which may be described as:

$$1/\lambda_{\text{abs}} = 1/\lambda_1 + 1/\lambda_2 + 1/\lambda_3$$

where λ_{abs} is the short wavelength of the absorber, and λ_1 , λ_2 and λ_3 are the laser incident beam wavelengths for the three wavelength case.

The laser 12 generates a pulsed output beam 16 which is scanned by an X-Y scanner 18 comprising a set of oscillating mirrors, and is then focused onto the specimen 14 at a focal point or volume 19 therein by a pair of eyepiece lenses 20 and 22, and an objective lens 24. The objective lens' back aperture is a pivot point for the scanned beam so, neglecting aberrations, all points in the raster pattern experience equivalent imaging conditions. The scanner 18 causes scanning of the focal point or volume 19 through the material 14, thereby causing fluorescence excitation of the material 14 at or near the focal point or volume 19.

Before the output beam 16 is directed into the X-Y scanner 18, it undergoes both dispersion compensation and pulse diagnostics. One complication of femtosecond pulsed illumination is dispersion. Short pulses tend to be broadened when passing through optical materials because differing frequency components of the pulse band width travel at different speeds within the materials. Dispersion compensation for optical materials is not essential for pulses greater than about 120 fsec, as these pulses have a small frequency band width (about 4 nm) and thus experience little spreading. However, a 700 nm, 70 fsec pulse is found to be spread about 1.5 times by a good objective lens, and substantially more by standard acousto-optical modulators that may be used for beam modulation and shutters. Pulse broadening reduces the observed fluorescence proportionality. In the microscope 10, dispersion compensation for optical materials is effected by a double pass through a pair of glass prisms 26 and 28 that direct the light so that the higher (in general slower) frequencies travel through less glass and are thus restored to the appropriate phase lag. A totally reflecting mirror 30 is employed to provide the return pass through the prisms 26 and 28.

For quantitative measurements, it is necessary to know the wavelength and pulse duration of the excitation beam, and thus various forms of pulse diagnostics 32 are provided to analyze the pulsed output beam 16. For a rough monitor of both wavelength and duration, a simple monochromator which, in its standard configuration, provides wavelength measurement, is

sufficient. If the output slit is removed and the resulting spectrum is sent to a screen or a one dimensional detector, the pulse wavelength band can be monitored. For a more precise pulse analysis, the pulse diagnostics 32 can comprise an autocorrelator which enables a direct, detailed measure of the pulse width and an indication of its phase coherence profile.

The laser microscope 10 also includes first, second and third dichroic mirrors 34, 36 and 38 which are employed to split off the fluorescence pathway for each of the three detector alternatives. The first of these alternatives is known as descanned confocal detection. In confocal detection, the fluorescence beam is descanned to form a stationary image plane at a pinhole aperture 40 placed before a confocal photomultiplier tube (PMT) 42. At every position in the scan, the point being illuminated in the sample focuses to, or is confocal to, the aperture in the detector plane. A band pass emission filter 44 is positioned between the pinhole aperture 40 and the first dichroic mirror 34 to eliminate undesired frequencies from the detected signals.

The second detection technique is known as Fourier plane detection in which the objective back aperture is focused through a lens 46 and a band pass emission filter 48 onto a Fourier PMT 50 without descanning. Because the back aperture is a pivot point in the scan, the fluorescence pattern is stationary at the photocathode.

Finally, the third detection technique is known as scanned imaging detection in which the entire focal plane in the specimen 14 is focused

through a band pass emission filter 52 and a focusing lens 54 onto an imaging detector 56, such as a CCD camera, whose acquisition speed is synchronized to the frame scan time.

5 The initial choice of detection method may be dictated by an existing microscope setup or by the microscopy method necessary for the specific experiments planned. Each detection scenario offers its own particular advantages and
10 disadvantages. In all of these detection scenarios, the collected fluorescence is extracted by an appropriately coated dichroic mirror. Because the difference between excitation and
15 emission wavelengths is typically much greater than the Stokes shift, the dichroic coating need not have the usual sharp cut-on between the reflection transmission bands. The emission
20 filters 44, 48 and 52 are usually standard, although they need to be checked for proper rejection at the multi-photon excitation wavelengths. Because the ratio of the average
25 excitation power to the fluorescence power is higher in multi-photon laser microscopy than in linear microscopies, a higher rejection ratio is required. Photomultiplier selection for a red-insensitive photoelectron emitter is therefore beneficial.

For multi-photon excitation with more than two photons, say with N photons, the number of
30 photons absorbed per pulse per fluorophore can be written generally as:

$$35 \quad N_{n_a} \approx \left[\frac{P_0^N N_\delta}{(\tau f)^{N-1} f} \left(\frac{A^2}{2hc\lambda} \right)^N \right]$$

where the pre-superscript N designates the number of photons simultaneously absorbed in analogy in the two photon excitation case where N=2 described above. The ratio $Nn_a / (N-1)n_a$ of successive rates for the multi-photon absorption process provides a useful comparison parameter of the form

$$\frac{Nn_a}{(N-1)n_a} = \frac{P_0}{(hc/\lambda)} \cdot \frac{1}{\tau f} \cdot \frac{N\delta}{(N-1)\delta} \cdot \frac{A^2}{2} \cdot \frac{1}{\lambda^2}$$

Favorable values of the expected absorption cross sections are tabulated below.

	Number of Photons n	(Area) ⁿ A ⁿ (cm ²ⁿ)	(coincidence time) ⁿ⁻¹ ($\delta\tau$) ⁿ⁻¹	Excitation Cross Section	Units
15	1	10 ⁻¹⁶ cm ²	1	$\sigma=10^{-16}$	cm ²
	2	10 ⁻³² cm ⁴	10 ⁻¹⁷ s	$\delta=10^{-49}$	cm ⁴ (s/ photon)
	3	10 ⁻⁴⁸ cm ⁶	10 ⁻³⁴ s ²	$\gamma=10^{-82}$	cm ⁶ (s/ photon) ²
20	4	10 ⁻⁶⁴ cm ⁸	10 ⁻⁵¹ s ³	$\epsilon=10^{-115}$	cm ⁸ (s/ photon) ³

With these typical values of the multi-photon cross sections and the instrument parameters described for two-photon excitation above, the absorption ratio is unity at about 3 W laser power. However, this equal emission power depends specifically on the wavelength dependent cross sections. Higher ratios $N\delta / (N-1)\delta$ exist for known favorable fluorophores and more may be found in

research motivated by this invention and by other applications of multi-photon absorption. In applications to biological cells and tissues, the selection of higher order multi-photon excitation process and optimization of excitation wavelength provides a means to select conditions suitable to minimize biological photodamage during fluorescence microscopy and microscopic activation of caged compounds. For multi-photon laser microscopy or photochemistry the selection of higher order multiphoton processes accommodates selection of available laser wavelengths.

With multi-photon excitation with $N > 2$ the imaging resolution is improved relative to two-photon excitation since the microscope point spread function, which defines resolution, is multiplied by itself to the power N . Thus for three-photon excitation the resolution is further improved by nearly the same factor as insertion of an infinitesimal confocal aperture, neglecting wavelength factors which do reduce resolution as wavelengths increase.

FIGs. 2 and 3 illustrate the fluorescence intensity as a function of the incident photon flux density for three-photon excitation of Fura-2 at $1.0 \mu\text{m}$, and Indo-1 with Ca at $1.0 \mu\text{m}$,

respectively. In both cases, the fluorescence intensity increases in proportion to the cube of the incident photon flux density, clearly indicating three-photon excitation in the test materials.

Another advantage of multi-photon excitation by three or more photons, is that the favorable properties of two photon excitation are further enhanced in higher order processes because dependence of out of focus excitation falls off as successively higher powers N of the intensity with increasing values of photon order N .

Since three or more photon excitation in accordance with the present invention provides access by visible or infrared light to excitation energies corresponding to single-ultraviolet-photon excitation, a whole new class of fluorophores and fluorescent indicators becomes accessible to three-dimensionally resolved laser scanning microscopy. Although three or more photon cross sections are not yet known for many compounds, and different selection rules apply to three or more photon absorption, molecular asymmetry often allows both odd and even photon transitions into the same excited state. It has been found that effects of excited state symmetry

do appear to shift the relative values of odd photon and even photon absorption cross section peaks. Thus, an absorption peak for two-photon absorption sometimes appears at a significantly shorter wavelength than twice the dominant absorption peak for the one-photon process, and the wavelength dependence of three-photon absorption can resort to a wavelength dependence like thrice the one-photon case. Multi-photon excitation may be particularly strong in the case of incoherent multi-step excitation where absorption of one energy (say by absorption of two-photons) reaches an intermediate state from which a subsequent additional photon provides the energy to reach a state from which fluorescence or photochemical activation can occur.

Now all of the above fluorophores are routinely used for imaging fluorescent label distributions in living cells with two-photon excitation. Three-photon excitation of comparable fluorescence intensities have been obtained with Indo-1, FURA-2, DAPI and darnyl. The three-photon absorption cross sections are approximately $3\delta \sim 2 \times 10^{-82} \text{ cm}^6 (\text{S/photon})^2$. Three- and four-photon excitation of fluorescent amino acids in serotonin, norepinephrine and tryptophan have

been measured with red light excitation with one-photon absorption occurring below 300 nm. The use of three- and four-photon excitation by available lasers provides an advantage in microscale
5 detecting and imaging of scarce neurotransmitters and hormones.

Another application of the present invention is as a method for producing microscopically localized ablation of tissue or tissue organelles
10 for their destruction or surgical removal. This is accomplished through use of the three or more photon absorption either by intrinsic chromophores, or by extrinsically provided chromophores that label the tissue and provide
15 first characteristic energies for absorption of subpicosecond pulses of laser light providing the second characteristic energy which is about an integer fraction, i.e., one third, one fourth, etc., or less of the first characteristic energy.
20 Alternatively, the molecules providing the necessary fluorescence can be intrinsic tissue fluorophores.

Although the present invention has been disclosed in terms of a preferred embodiment, it
25 would be understood that numerous modifications and variations could be made thereto, without

18

departing from the scope of the invention as
defined in the following claims.

Claims

1. A method of microscopy by a three or more photon excitation technique of a target material containing molecules which are excitable by
5 photons of a characteristic energy comprising the steps of:

illuminating said material with a beam of intense, subpicosecond pulses of laser light comprising photons of an energy approximately $1/n$
10 of said characteristic energy, where n equals a number of photons to be absorbed by said material and is greater than or equal to three; and

focusing said illumination within said material to produce an illumination intensity
15 sufficiently high to produce molecular excitation by simultaneous absorption of at least three of said incident illuminating photons.

2. The method of claim 1, wherein said material includes cages biologically active
20 molecules, said illumination intensity being sufficient to release caged biologically active compounds by simultaneous absorption of n incident photons, each of energy equal to approximately $1/n$ of said characteristic energy.

3. The method of claim 1, wherein said material includes fluorescent molecules, said illumination intensity being sufficient to produce fluorescence of said material by simultaneous
5 absorption of n incident photons, each of energy equal to approximately $1/n$ of said characteristic energy.

4. The method of claim 3, wherein said step of focusing said illumination further comprises
10 focusing said illumination to a small focal volume within said material to produce illumination intensity sufficiently high only at said focal volume to produce molecular excitation by simultaneous absorption of said n of said incident
15 illuminating photons.

5. The method of claim 4, further including the steps of:

scanning said beam to scan said focal volume through said material; and
20 detecting the fluorescence produced by said material.

6. The method of claim 1, wherein said material is a tissue, and said molecular

excitation occurs by simultaneous absorption of at least three of said incident illuminating photons by intrinsic chromophores, extrinsically provided chromophores or intrinsic fluorophores within said tissue.

7. An apparatus for laser scanning fluorescence microscopy of a target material including a fluorescent component responsive to excitation by photons of a characteristic energy to produce fluorescence photons, said apparatus comprising:

stage means for receiving said target material;

at least one source of subpicosecond coherent light pulses comprised of energy $1/n$ of said characteristic energy, where n is greater than or equal to three;

means for focusing said coherent light pulses on said target material, thereby causing said target material to absorb at least three photons and produce said fluorescence photons;

detector means for detecting said fluorescence photon; and

means for directing said fluorescence photons to said detector means.

8. The apparatus of claim 7, further including scanning means for scanning said light pulses through said material.

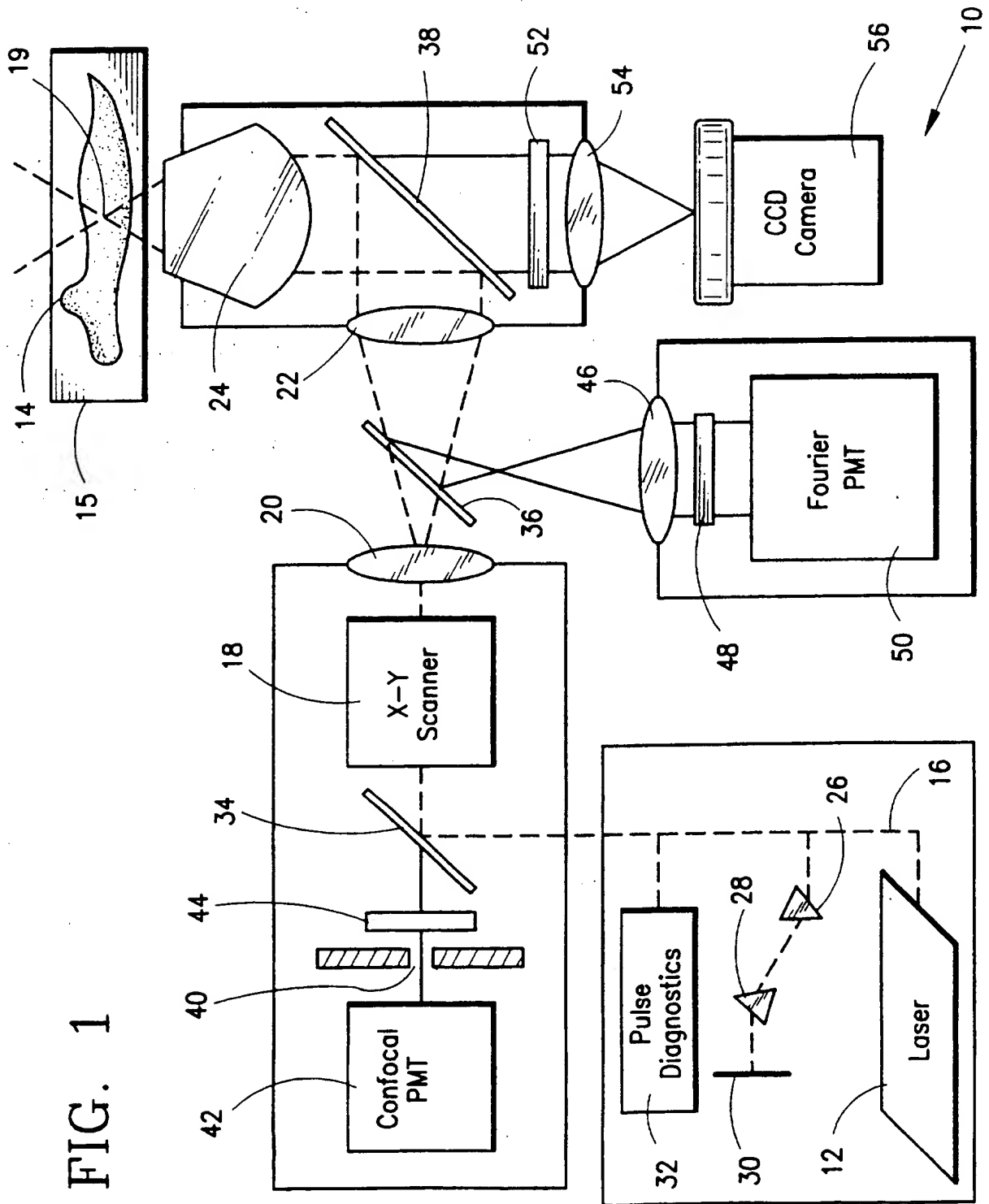
9. The apparatus of claim 7, wherein said
5 detector means comprises a confocal photomultiplier tube.

10. The apparatus of claim 7, wherein said detector means comprises a Fourier plane detector.

11. The apparatus of claim 7, wherein said
10 detector means comprises an imaging detector.

1 / 3

FIG. 1



2 / 3

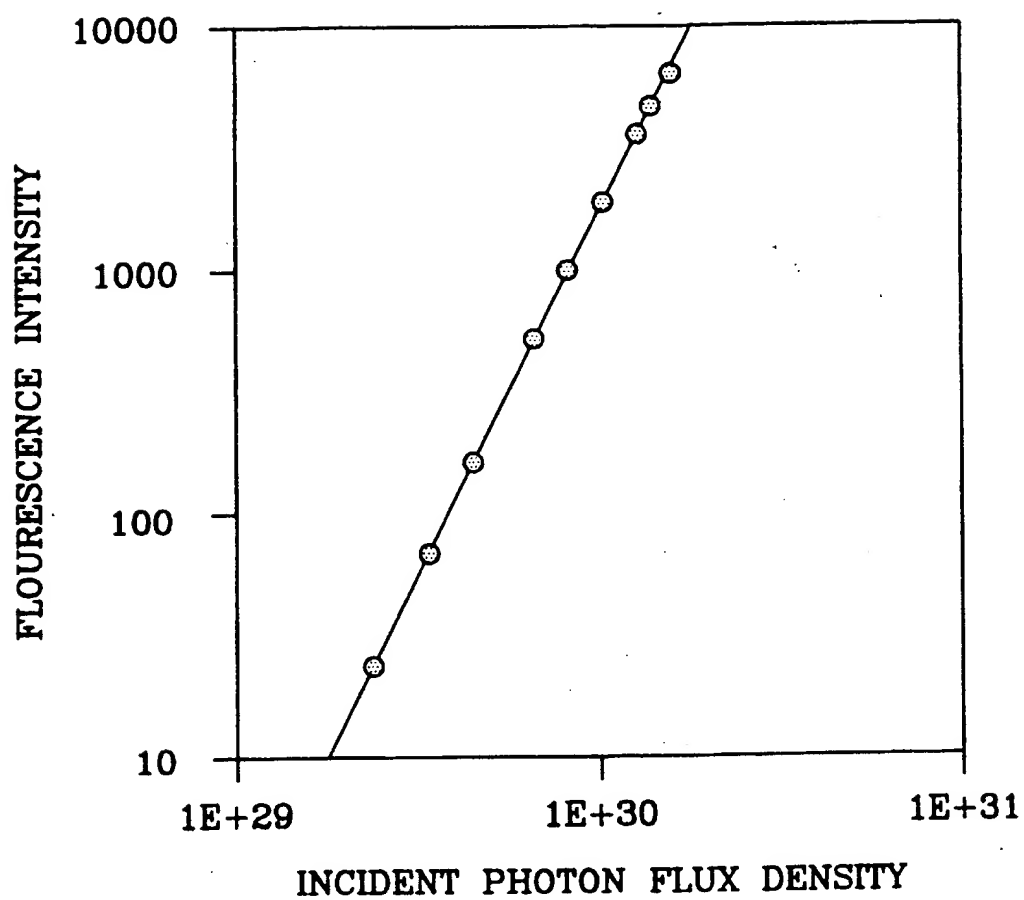


FIG. 2

3/3

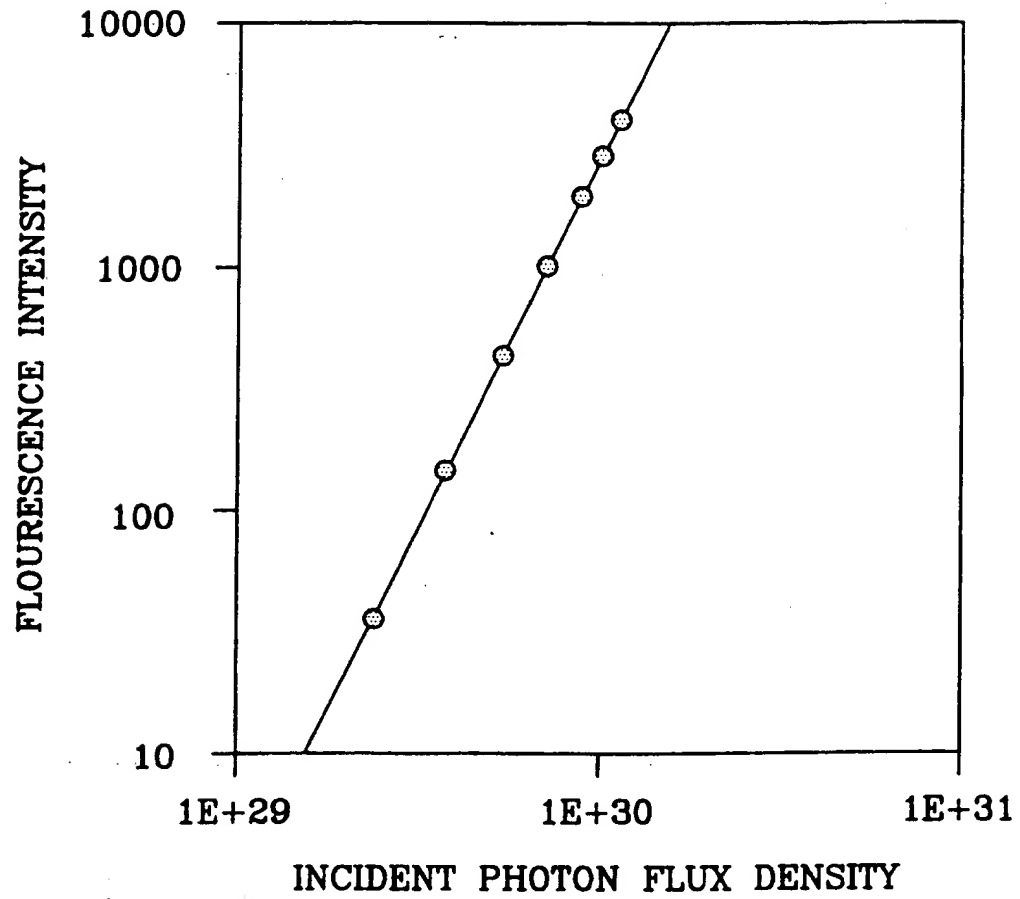


FIG. 3

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US96/14519

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) : G01N 21/64

US CL : 250/458.1; 459.1

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 250/458.1; 459.1, 461.1, 461.2

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

APS search terms: (two or three or multi)(w)(photon)(w)(absorption or excitation or fluorescence) and (laser(p)
?picosecond pulse#)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US, A, 5,034,613 (DENK et al) 23 July 1991, see entire document.	1-11
A,P	US, A, 5,523,573 (HANNINEN et al) 04 June 1996, see entire document.	1-11

☐ Further documents are listed in the continuation of Box C.☐ See patent family annex.

* Special categories of cited documents:

A document defining the general state of the art which is not considered to be of particular relevance

E earlier document published on or after the international filing date

L documents which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

O document referring to an oral disclosure, use, exhibition or other means

P document published prior to the international filing date but later than the priority date claimed

T

later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

X

document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

Y

document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

&

document member of the same patent family

Date of the actual completion of the international search

18 OCTOBER 1996

Date of mailing of the international search report

31 OCT 1996

Name and mailing address of the ISA/US
Commissioner of Patents and Trademarks
Box PCT
Washington, D.C. 20231

Facsimile No. (703) 305-3230

Authorized officer

EDWARD J. GLICK

Telephone No. (703) 308-4858